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Magnetic anisotropy and magnetoelastic properties of $Fe_{10}Ni_{90}$ films

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Abstract. This work is devoted to studying the effect of the thickness and type of the buffer sublayer on the magnetic anisotropy and the magnetoelastic properties of $Fe_{10}Ni_{90}$ films. It is established that the anisotropy of Fe films strongly depends on thickness, which can be associated with the influence of several mechanisms of anisotropy formation. Measurements of the magnetostriction of thin films using magnetoresistive curves were made. The value of the magnetostriction constant also depends on the thickness of the films.

1. Introduction

3d-metal films are known for their many unique properties, allowing them to be widely used in practical applications [1]. These films can have both a large magnetostriction and high anisotropic magnetoresistance [2]. Due to this combination of effects, the functionality of the film media greatly increases. A striking example of the technical application of media combining anisotropy of magnetoresistance and magnetostriction are pressure and strain sensors [3]. At the moment, the most interesting area of application of these film media are composite layered multiferroics [4]. In such structures, a large magnetoelectric coupling coefficient is achieved. However, at the moment, the technical application of composite multiferroics is difficult due to the use of materials with a large coercive force as the magnetostrictive component [5,6]. This disadvantage lacks a film of composition $Fe_{10}Ni_{90}$, which has an acceptable magnetostriction (~ 20 ppm) and a low coercive field (~ 5 Oe). However, some of the important properties of these thin film media can be very different from bulk materials. In this work, we studied the effect of the thickness and type of the surface on which the film was deposited on the magnetic and magnetoelastic properties of $Fe_{10}Ni_{90}$ films.

2. Samples and techniques

$Fe_{10}Ni_{90}$ films were obtain by RF-sputtering in a technological field of 200 Oe, which set the technological field axis (TFA) in the plane of the substrate. Corning cover glasses 0.2 mm thick were used as substrates. The thickness of the $Fe_{10}Ni_{90}$ films varied from 10 to 120 nm, and the thickness of the Ta buffer layer was 5 nm. A spin coater was used to obtain a PVDF sublayer 200 nm thick on a glass substrate. Magnetic properties were measured on a LakeShore VSM 7407 and Kerr-microscope Evico-magnetics. Magnetoresistive loops were measured by the standard four-probe method of measuring the electrical resistance in a magnetic field up to 200 Oe. Samples for magnetoresistive measurements were

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cut in the form of strips with dimensions of 2x15 mm with the TFA oriented either along or perpendicular to the long side of the strip. An indirect method was used to study the magnetoelastic properties, based on the analysis of changes in magnetoresistive loops during bending of the sample. The deformation of the strips was carried out by controlled bending. The applied strain had a compressive nature since the film was on the inner surface of the bend substrate (figure 1). A digital micrometer was used to measure the deflection δ (up to 120 μm), which was then converted into relative linear deformation $\varepsilon = \Delta l/l$ using the formula:

$$\varepsilon = 4\delta d/L^2 \qquad (1)$$

where L is the distance between the supports, which was 12 mm in our case, and d is the thickness of glass substrate.

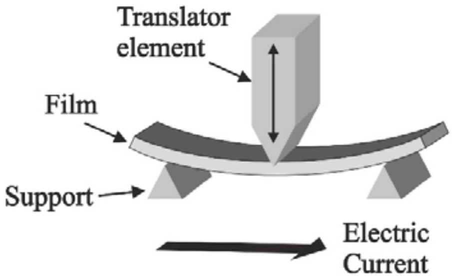

Figure 1. Schematic representation of the magnetostriction measurement geometry.

3. Results and discussion

3.1. Magnetic anisotropy of $Fe_{10}Ni_{90}$ films

Figure 2 shows the magneto-optical hysteresis loops of $Fe_{10}Ni_{90}$ films of various thickness, measured along (curves 1) and perpendicularly (curves 2) to the TFA.

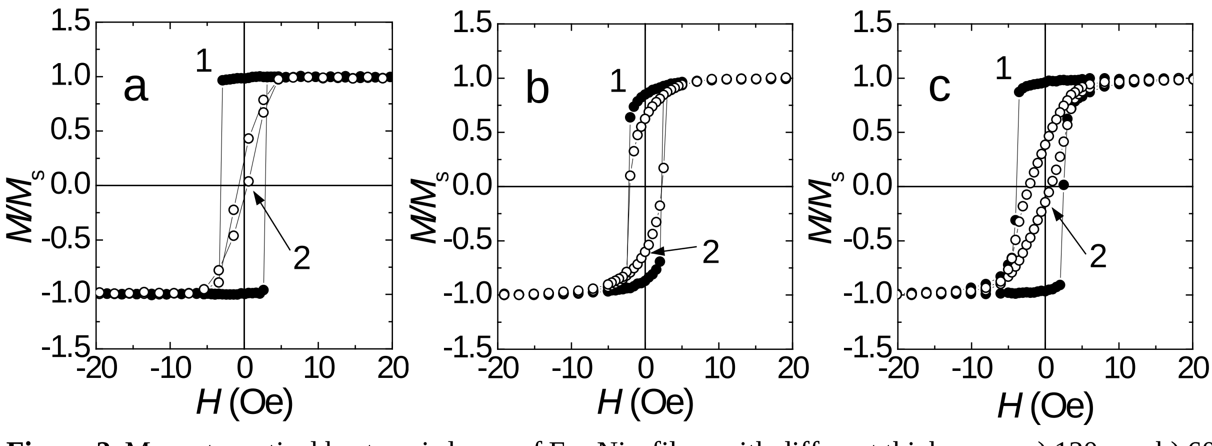

Figure 2. Magneto-optical hysteresis loops of $Fe_{10}Ni_{90}$ films with different thicknesses a) 120 nm, b) 60 nm, c) 20 nm, measured along (curves 1) and perpendicular (curves 2) of the TFA.

As can be seen from the loops shown in figure 2, the magnetic anisotropy can vary greatly depending on the film thickness, as evidenced by the shape of the loops and their coercive field in different directions. In the case of thick films (~ 120 nm), a good uniaxial anisotropy is formed (figure 2a). With a reducing in the film thickness, the apparent uniaxial anisotropy disappears and in the plane the sample becomes almost isotropic (figure 2b). However, at low thicknesses of the order of 20 nm (figure 2c), a pronounced uniaxial anisotropy appears again.

This fact of a change in the anisotropy of films with thickness can be explained by the action of two or more mechanisms for the formation of anisotropy in films, for example, such as magnetoelastic and magnetostatic. The behavior of the loops in figure 2 can also indicate that with a change in the thickness of the films, the contribution from these mechanisms can be different, which causes a non-monotonic change in anisotropy. The competition of these mechanisms of anisotropy formation occurs through the defect structure of the film. The magnetostatic contribution arises due to the formation of anisotropic grains in the film under the action of the technological field during sputtering. So with large film thicknesses, grains are fully formed and it acquires a magnetostatic mechanism for the formation of anisotropy. The magnetoelastic contribution arises due to the presence of significant mechanical stresses at the interface of the film with the substrate and the presence of a significant negative magnetostriction constant for the $Fe_{10}Ni_{90}$ films. It is logical to assume that the effect of mechanical stresses will decrease with increasing film thickness and, therefore, the magnetoelastic contribution will weaken. Due to the presence of a negative magnetostriction constant and anisotropy of the defect structure for films with a thickness of about 60 nm, the magnetoelastic contribution can form the anisotropy axis perpendicular to the TFA. As a result, due to the competition of the magnetoelastic and magnetostatic contributions to the anisotropy, an almost isotropic state can arise. For thin films with a thickness of about 20 nm, the grains may not be completely formed, which does not make the magnetoelastic contribution manifest. As a result, we can again observe uniaxial anisotropy, but less pronounced than for thick films.

Since the loops shown in figure 2 are measured locally and carry information only about the surface of the film, it is advisable to compare them with magnetometric loops measured using a VSM, which reflect the integral (from the whole volume) magnetic properties. Figure 3 shows the magnetometric hysteresis loops of the $Fe_{10}Ni_{90}$(60 nm) film obtained using a VSM.

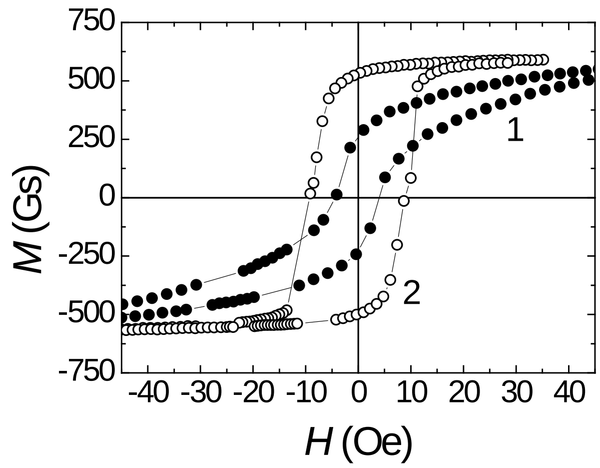

Figure 3. Magnetometric hysteresis loops of $Fe_{10}Ni_{90}$ film with thicknesses 60 nm measured along (curves 1) and perpendicular (curves 2) of the TFA.

As can be seen from figure 3, at a thickness of 60 nm, anisotropy is formed predominantly perpendicular to the technological field, which confirms the assumption that there is a competition between several mechanisms for the formation of anisotropy. This difference at a thickness of 60 nm in magneto-optical and magnetometric loops can be the result of a non-uniform distribution of magnetization, and, therefore, anisotropy, across the thickness of the film.

To estimate the uniaxial anisotropy, we introduced the Δ_a parameter, which characterizes the coercive field anisotropy and is calculated using the formula:

$$\Delta_a = 100\% \cdot (H_{c\_along} - H_{c\_perp}) / H_{c\_along} \tag{2}$$

where H_{c_along} is the coercive field of the loop, measured along the TFA, H_{c_perp} is the coercive field of the loop, measured perpendicular to the TFA.

Figure 4 shows the dependence of the Δ_a parameter on the thickness of the $Fe_{10}Ni_{90}$ films deposited on glass substrate or pre-sputtered tantalum buffer layer.

As can be seen from figure 4 (curve 1), with thicknesses in the range of 90-120 nm, uniaxial anisotropy is formed, after which there is practically no anisotropy in a wide range of thicknesses from 30 to 80 nm. At small thicknesses in the region of 20 nm, uniaxial anisotropy reappears, after which it disappears at lower thicknesses, which may be due to the film structure that is not fully formed. The deposition of films on the Ta sublayer allows one to preserve uniaxial anisotropy over almost the entire thickness range, which may be a consequence of reducing the effect of mechanical stresses from the substrate, which form the magnetoelastic contribution to anisotropy.

Summarizing the above, we can conclude that the anisotropy in $Fe_{10}Ni_{90}$ films is complex and strongly depends on the film thickness. To establish the mechanisms affecting anisotropy, additional research is needed.

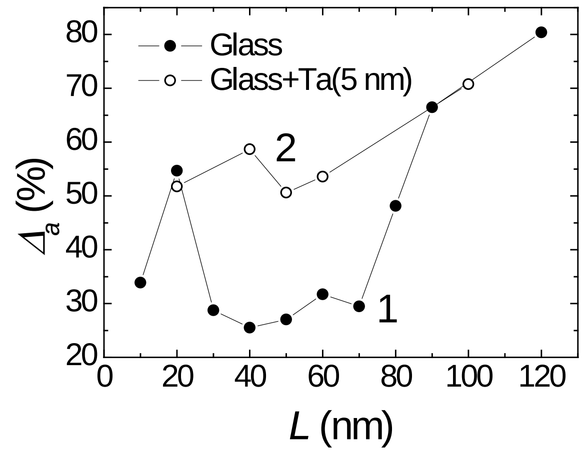

Figure 4. Dependence of the Δ_a parameter on the film thickness deposited on glass (curve 1) and on glass with a Ta underlayer with a thickness of 5 nm (curve 2).

3.2. Magnetoelastic properties of $Fe_{10}Ni_{90}$ films

To measure magnetostriction, stripes of $Fe_{10}Ni_{90}$ films with the TFA along the long side were used. Magnetostriction was determined by an indirect method by changing the magnitude of the anisotropy field. Figure 5 shows the magnetoresistive loops of the $Fe_{10}Ni_{90}$ film measured perpendicular to TFA in the initial state and with deformation.

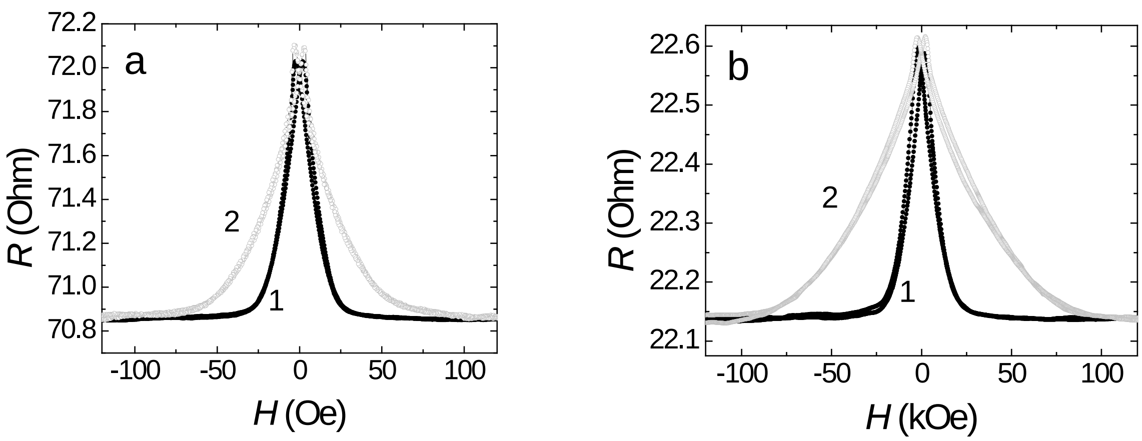

Figure 5. Magnetoresistive loops measured perpendicular to TFA in the initial state (curve 1) and with a relative compressive strain of 0.055% (curve 2) for film $Fe_{10}Ni_{90}$ with thickness a) 40 nm, b) 80 nm.

As can be seen in figure 5, magnetoresistive loops are significantly transformed by the application of deformation, in particular, this is manifested in a change in the anisotropy field. This change is associated with an increase in the effective anisotropy constant due to the action of the negative magnetostriction constant. You can also note that for a thicker film (figure 5b), this change is much larger than for a thin one (figure 5a). This fact can be associated with the presence of significant inhomogeneity of magnetization in thin films, which becomes insignificant at large thicknesses. To determine the value of the magnetostriction constant from magnetoresistive loops, the change in the anisotropy field ΔH_A was determined. Since the entire change in anisotropy is related to the magnetoelastic contribution, the value of the magnetostriction constant can be determined by the formula [7]:

$$\lambda_s = (1/3)\cdot\Delta H_A\cdot M_s/\sigma \tag{3}$$

where λ_s is magnetostriction constant, M_s is saturation magnetization, σ- mechanical stress.

By the formula (3), the values of the magnetostriction constant λ_s are determined, which are $-1\cdot10^{-5}$ and $-2\cdot10^{-5}$ for films of 40 nm and 80 nm, respectively. The obtained value of the magnetostriction constant for a film with a thickness of 80 nm is close to the values for bulk material of this composition.

3.3 Anisotropy of PVDF/$Fe_{10}Ni_{90}$ composites

Figure 6 shows the magneto-optical hysteresis loops of the PVDF/$Fe_{10}Ni_{90}$ composite measured along and perpendicular to the TFA.

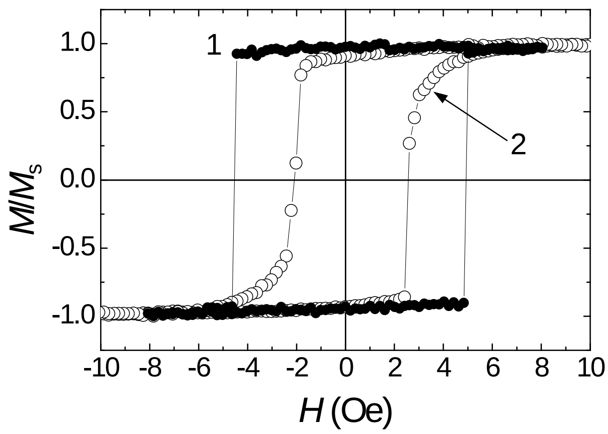

Figure 6. Magneto-optical hysteresis loops of PVDF/$Fe_{10}Ni_{90}$ films with thicknesses 200 nm and 100 nm respectively measured along (curves 1) and perpendicular (curves 2) of the TFA.

Analyzing the hysteresis loops shown in figure 6, we can conclude that the uniaxial anisotropy of the $Fe_{10}Ni_{90}$ film deposited on the PVDF polymer layer is preserved predominantly. Soft magnetic properties of the $Fe_{10}Ni_{90}$ layer are also preserved. This fact optimistic forecasts for the use of $Fe_{10}Ni_{90}$ films in composite multiferroics.

4. Conclusion

In the framework of this work, it was established that the nature and magnitude of the magnetic anisotropy of $Fe_{10}Ni_{90}$ films strongly depends on their thickness. This is associated with the competition of the magnetoelastic and magnetostatic mechanisms of induced anisotropy.

For films with a thickness of about 60 nm, a perpendicular orientation of the anisotropy axis with respect to the technological field can be observed.

The tantalum sublayer with a thickness of 5 nm significantly improves the uniaxial anisotropy of Fe films over the entire thickness range, which is associated with a decrease in the magnetoelastic contribution to the film anisotropy.

It is shown that the magnitude of the magnetostriction constant in films with a thickness of 80 nm is $-2\cdot10^{-5}$, which is acceptable for use in composites with a magnetoelectric effect.

Also, the anisotropy and magnetic properties of the $Fe_{10}Ni_{90}$ layer of test composites are preserved.

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